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PHOTOGRAPHIC METHODS FOR DETERMINATION OF DROPLET SIZE SPECTRA

G. Jandl and O. Bell

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16. Abstract

Drop spectra arising from oil atomization cannot be calculated, but must be measured. Of the possible methods, short-time flash photography was selected, on consideration of the conditions in heating oil atomization, and tested. The method raises problems in illuminating technology, primarily due to the fact that light intensities from spark flash equipment decrease with shorter flash times. A photographic system is proposed which makes possible short-time photography of droplets with continuous light.

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PHOTOGRAPHIC METHODS FOR DETERMINATION OF DROPLET SIZE SPECTRA /313*

G. Jandl and O. Bell

Statement of Problem

In process technology, liquids are often atomized. This type of preparation has quite different objectives.

Atomization has particular importance in preparation of liquid fuels. The great specific surface attained in this way is the requirement for rapid heating and mixing with the combustion air, and, therefore, for high energy conversion.

Studies in flame research have shown that, along with other factors, the differing particle sizes which arise from fuel atomization also have a decisive influence on the combustion process. This influence extends from the ignition behavior through the temperature distribution in the flame, and the radiation ability to the final combustion of a flame [1].

An average drop diameter obtained by calculation says nothing about the range of variation and the composition of a drop spectrum, so that it cannot suffice as a measure of evaluation for quantitative understanding of the relations. On the other hand, it is impossible to calculate the drop size and the numerical composition of a mixture of droplets arising

* Numbers in the margin indicate pagination in the original foreign text.

in the stochastic process of fuel atomization. The drop spectra, then, must always be analyzed by measurement.

Methods of Measurement

The objective in drop size analysis is to classify the drops in the spectrum of a set of drops into various fineness classes, depending on their size, and to determine the number / 314 of drops in each class.

The methods for drop size analysis described in the literature can be assigned to three groups:

- collection methods
- fractionating separation methods
- optical methods.

Collection methods

In this method, a collection device is either moved quickly through the atomizer jet or it is exposed briefly to the jet by means of a shutter, like that in a camera [2, 3].

In all collection methods the flow conditions are disturbed. This leads to errors in measurement because the portion of smaller drops which can deviate to follow the disturbed flow following the collection surface is not considered in the measurement. One common source of error in the direct method is that the drops break up on impact, or that they run together with other drops [4]. The indirect methods, in which one uses a comparison liquid, do not all exact quantitative statements because as a rule the important material characteristics (viscosity, surface tension, density) do not agree with those of the comparison liquid [5, 6].

Fractionating Separation Methods

These methods separate the atomizer jet. They are used primarily in aerosol technology and are of minor importance for atomization of fuel oil [7, 8].

Optical Methods

The methods mentioned previously have the common feature that they must collect or separate the drops to be studied in some manner. The decisive advantage of the optical methods is in their non-contact measurement.

Photographic Methods

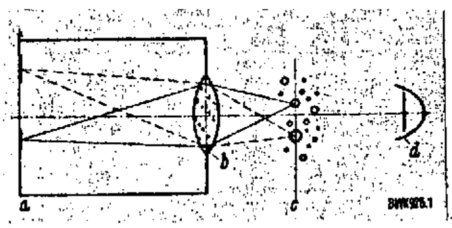

Figure 1. Essential arrangement of camera and flash lamp for droplet photography.

a. Film plane b. Optics
c. Ideal plane of sharpness
d. Flash lamp

In droplet photography, a section of the atomized oil jet is photographed with a photomacrographic system using back-lighting, Figure 1. A flash system must be used as the light source to give short exposure times matching the drop velocity.

Holographic Methods

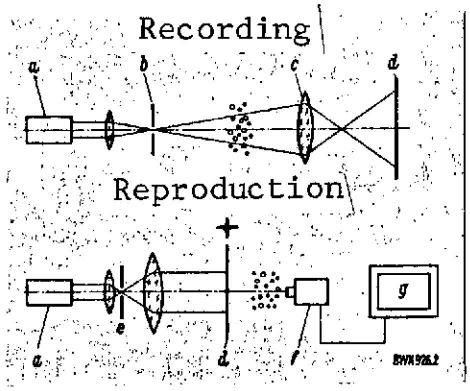

Figure 2. Principle of holographic particle size determination [9].

a. Laser
b. Aperture
c. Objective
d. Hologram
e. Collimator
f. TV camera
g. Monitor

In order to record holograms of fast-flying droplets, Figure 2, high-power pulse lasers giving short flashes of coherent light are used [9].

After passing the particles, those light waves which pass the drops undisturbed mix with the spherical scattered light waves from the particles. The resulting interference figures, always consisting of concentric, alternately bright and dark rings, are recorded on a photographic plate. If one illuminates the hologram thus obtained with parallel laser light, one again obtains a real image of the actual drops. The drop images are measured on the monitor.

With the holography method, droplets from 1 μm to some 1 mm in diameter can be measured. Along with the high cost of equipment, there is also a high expenditure of time in this method because of the slow evaluation of the holograms.

Light Scattering Methods

The measuring principle is based on the fact that the intensity of the scattered light produced by a particle (droplet) is a measure of its size [10]. The particle size spectrum is obtained by classifying the scattered light pulses by their height. The equipment is calibrated with test aerosols of known particle size.

Short-Flash Photographic Method

In a practical evaluation of atomization measuring methods, the short-flash photographic method proves best. The advantages are:

- non-contact measurement without affecting the atomizer jet;
- many pictures can be obtained from different places in the atomizer jet without a large expenditure of time;
- the cost is low in comparison to other optical methods.

In comparison to some special aerosol measuring methods, the lower limit of the measuring range is high. But there are still no universal measuring methods which can give higher resolution over the same range of measurements under the conditions prevailing in heating oil atomization.

Light source

According to Michel [6], the droplets are imaged sharply enough for measurement if their movement during illumination is no more than 10% of their diameter. Along with the droplet velocity, the drop size also affects the illumination period required for photography. Figure 3 shows the relation for the velocity range of interest. / 315

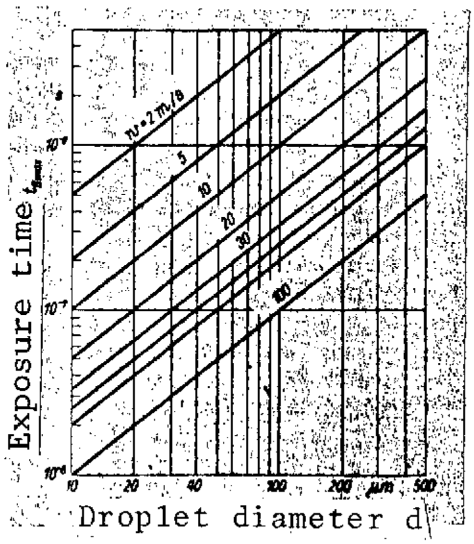

Figure 3. Maximum allowable illumination time as a function of the particle size and particle velocity.

$t_{B\,max} = 0{,}1\, d/w$

Flash times in the range from 10^{-5} to 10^{-8} seconds make use of spark flash equipment necessary. As the flash times become shorter, one must accept a considerable loss of flash energy, which is expressed as a lower intensity for the light source.

To get the highest possible light intensity, the light source and the camera optics must be as closely adjacent to each other as possible. It is helpful to use a condensor for concentrating the light.

The fact that the section of the jet to be photographed must be selected at a large distance from the nozzle has a bad effect on the illumination intensity, as the velocity and concentration of the droplets are lower here. Because of the larger diameter of the spray cone, however, the distance between the camera and the flash lamp must be greater.

Film

The resolving power of a photographic emulsion decreases as its sensitivity increases. The values in Table 1 apply to black and white materials under favorable conditions.

Table 1. RESOLVING POWERS OF BLACK AND WHITE PHOTOGRAPHIC MATERIAL [11].

DIN sensitivity	lines/mm
6 to 10	200 to 500
11 to 16	185
17 to 20	150
21 to 24	80
24 to 40	$\leq$ 80

If one avoids the use of extremely sensitive materials because of their low resolving power and takes a moderately sensitive type in the range of 21 to 24 DIN, then the necessary scale of reproduction can be estimated if one specifies the smallest particle size which must be resolved. The resolving power of 80 lines/mm corresponds to a line separation of about 12 μm. As the droplets are imaged at the scale M, then

$$M \cdot d_{min} \approx 12\ \mu m.$$

If one chooses $d_{min} = 4\ \mu m$, then we get the magnification:

$$M \approx 3:1$$

For photographic emulsions, the exposure, B, can to a first approximation be represented by the time integral

$$B = \int_0^{t_B} E\,dt$$

Here E, in lux, is the illumination intensity and t_B in seconds is the exposure time.

The density, S, of the developed emulsion is related to the exposure, B, through the density curve, Figure 4.

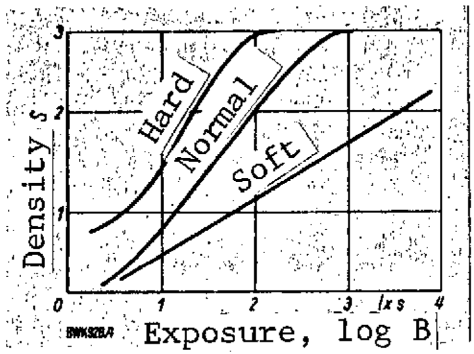

Figure 4. Different density curves as a result of different development times [12].

Contrast $\gamma = \frac{\Delta S}{\Delta \lg B}$

The most favorable working region is in the linear part of the density curve. The slope of the curve in this region is called the contrast, γ, of the photographic emulsion. It is a measure of the possible contrast.

It is necessary to use a film having high contrast under normal exposure and development conditions in order to get usable contrast in short flash photography.

Overly long development times (hard development) give increased contrast, to be sure, but at the same time this is linked with an increase of base fog (blackening of unexposed areas). But in the "shadow photography" of droplets, this leads to reduction in the contrast.

Camera Optics

Because of the effect of the spray, one is forced to place the camera optics at sufficient distance from the envelope of the spray cone. In order to be able to make enlarged photographs of oil droplets, even in the region of the jet axis, from this position, a correspondingly long focal length must be selected, Figure 5.

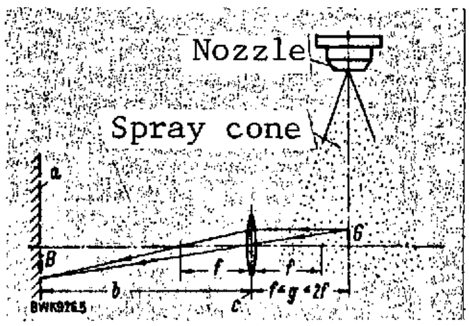

Figure 5. Arrangement for enlarged imaging of oil droplets.

a. Photographic emulsion
b. Picture width
c. Lens plane for camera optics
f. Focal length
g. Object width
B. Image
G. Object

Reasonable values for the focal length are in a range from f = 100 to 150 mm. The most symmetrically designed Macro or Repro objectives possible should be used, because these are corrected for short distances. Admittedly, such objectives are not very fast.

For two reasons, the work should be done with the widest possible aperture:

a) The greater light flux leads to a greater illumination intensity.
b) The depth of field is less. Droplets in or only a little outside the ideal plane of sharpness can then be distinguished better from those farther outside, although the transition is always gradual. The probability that several droplets will be superimposed at equally sharp focus decreases.

Experiments

Photographic Equipment

On the basis of the selection criteria presented, the following equipment was used:

a) Camera:
   Exakta Varex IIb miniature reflex camera with an f/4 100 mm telephoto objective and the necessary extension. Corresponding to the camera format, the section covered by the optics has an area of about 8 x 12 mm^2.
b) Light source:
   Ultra-short flash lamp, Type 8N 12L with trigger device [13]. Technical data:

Flash duration (half peak width)	18 ns
Rise time (10-90%)	4 ns
Energy per flash	25 mJ

The effect of outside light was eliminated by darkening the test stand.

c) Film

Kodak 2474 Shellburst Film

Developer: Kodak Type D-19

Atomizer /316

Figure 6 shows a comparative survey of the number-frequency distributions occurring with the various methods of atomization. According to this, injection atomizers

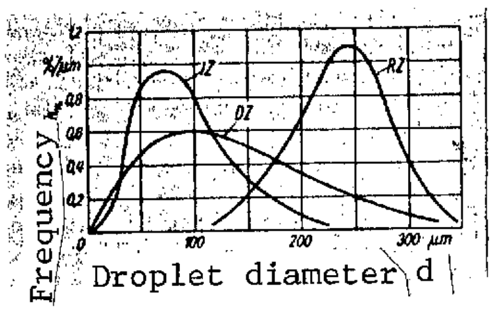

Figure 6: Particle size distribution for various atomizer systems [14].

IZ Injection atomizer
RZ Rotation atomizer
DZ Pressure atomizer

yield the smallest droplets, with droplet diameters of about 60 µm. Because of the difficulties in imaging small droplets mentioned above, it appeared reasonable to test the short-flash method on injection analyzers.

For the tests, we used atomizer nozzles which are known commercially as "Y-atomizers" because of their design (Figure 7). Air was the atomization medium.

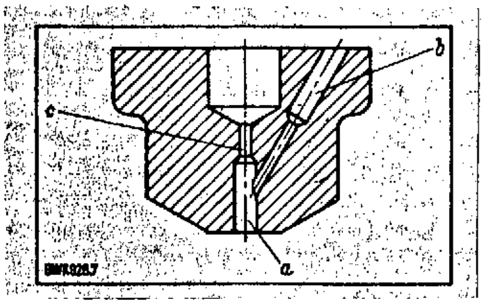

Figure 7. Section of a Y-nozzle.

a. Mixing chamber hole d_A
b. Oil hole
c. Air or steam hole.

Sample photographs showed that the light absorption of the atomizer jet was too great. The drop pictures were seriously underexposed and had too little contrast for evaluation. For that reason, we used two rectangular drop collection tubes to separate a "slice" of the atomizer cone, through which enough light from the flash lamp penetrated (Figure 8).

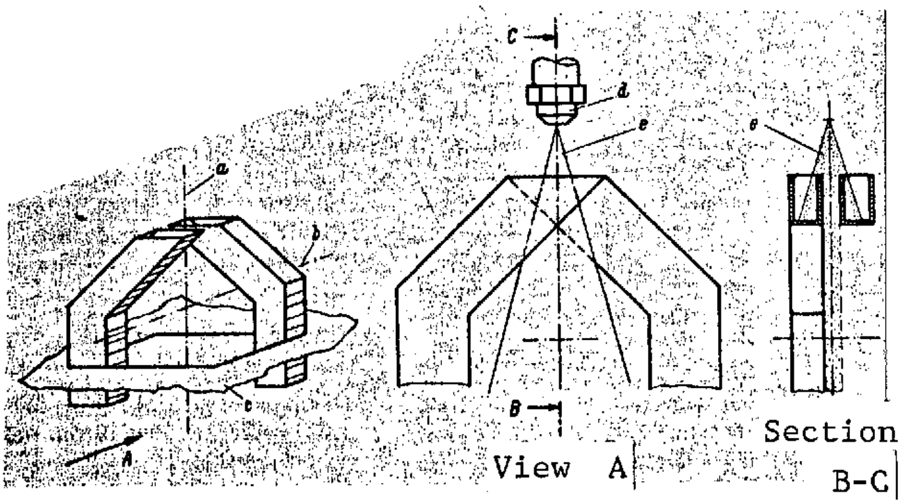

Figure 8. Arrangement of drop collecting tubes to separate a slice from the spray cone.
a. spray cone axis. c. cover e. spray cone
b. optical axis of lamp and camera d. nozzle.

Evaluation

Figure 9 shows the problems of counting and classification. The gray tone becomes lighter the farther the droplets are from the zone of sharp focus. Choice of droplets to be considered must, then, be made by judgement, i. e., subjectively. That

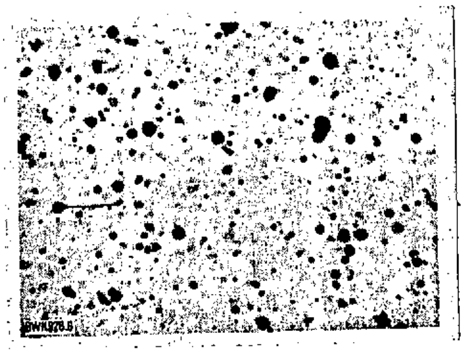

Figure 9. Section of a photograph of light oil droplets; M = 25:1.

is the disadvantage of manual evaluation.

Therefore, we attempted to "filter out" the sharply imaged, that is, the dark, droplets, by a photographic separation method [15]. This method requires recopying on special film. It does not, however, give the desired success. The problem is only moved. The pictures obtained could be evaluated well, to be sure, but uncontrollable errors occur in respect to the number of drops and their size relations (Figure 10).

The problem could be solved by use of a completely automatic image analysis computer (Figure 11).

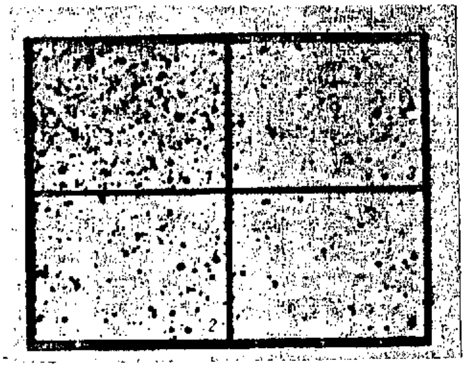

Figure 10: Original (1) and various tone separation stages (2 to 4) (section of a photograph of heavy oil droplets).

By means of an optical system, a real image of the droplet picture was projected upon the light-sensitive layer of a special TV camera. An electron beam samples the image in points. As each of the 720 lines is broken up into 910 image points, the raster image consists of about 650,000 points.

The brightness fluctuations of the picture are converted through the sampling into corresponding voltage variations, which arrive at adjustable detectors. The pulse height discriminators (IHD) can pass only those signals which exceed the prescribed pulse height; i. e., those signals originating at parts of the picture with a certain minimum density. In this manner, the video signal is converted into a pure black and white signal.

The threshold value for the pulse height discriminator is adjusted so that the particle size is not changed by the pulse height discrimination. This is checked by rapidly switching the monitor so that both the pictures generated before and after the discriminator superimposed briefly.

The black and white signal coming from the pulse height discriminator now goes to the pulse width discriminator (IBD). Because of the constant scanning rate, the pulse width is proportional to the chord length in the line direction. Pulses may be assigned to the individual particles by comparing signals from two adjacent lines using memories and gates.

The instrument gives reproducible results and makes possible rapid and precise evaluation of the droplet pictures. It measures the drop diameters fully automatically, classifies them, and prints out the results.

As the computer does not process physical length units, but "image point units", the true length for one image point 317
unit was determined by a calibration measurement. At a

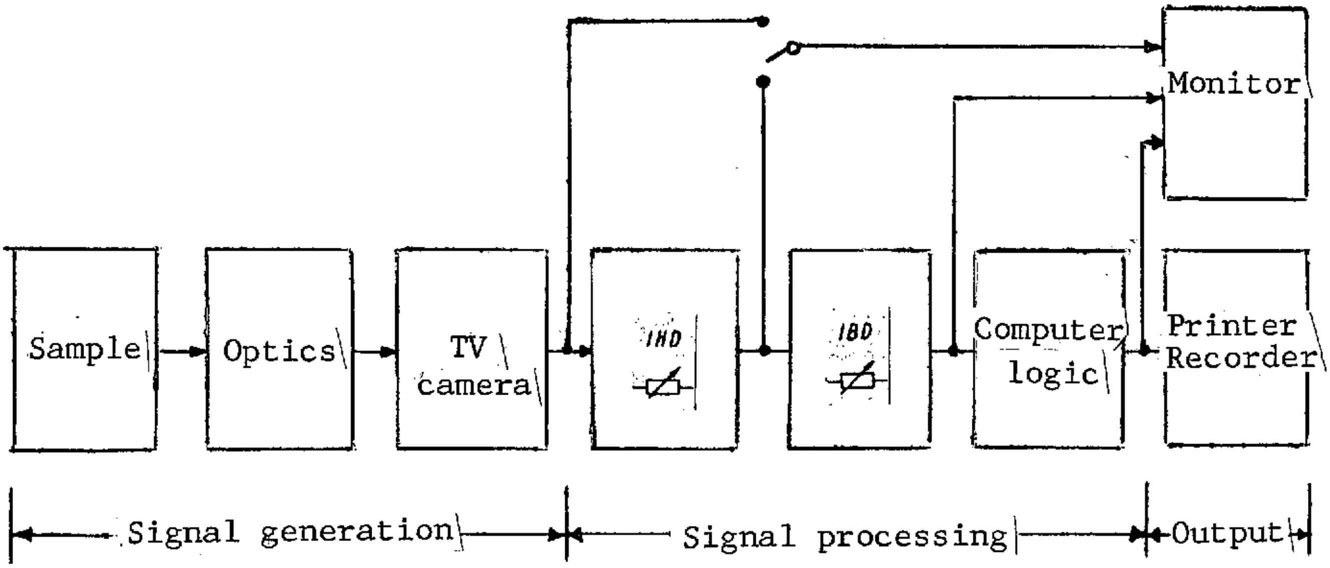

Figure 11. Schematic structure of the "Quantimet 720" [16].

magnification of 25:1 for the droplet photograph, this was 4.65 μm per image point, and 3.88 μm per image point for a magnification of 30:1. Thus, the smallest resolvable drop diameter, d_{min}, was 4.65 μm or 3.88 μm, respectively.

Proposal for Short Time Photography in Continuous Light

It is also possible to use a continuous light source for short time photography if an appropriately fast camera shutter ensures a sufficiently short exposure time.

In comparison to the short time flash method, drop photography in continuous light has the advantage that it is possible to use a light with its intensity matched to the photographic problem. The experimental cost can also be reduced markedly:

- the light source can be placed so that it is not affected by the spray cone;
- adjustment of the camera and light source are less critical. It can be performed easily, as the beam path of the light can be followed well;
- because of the higher light intensity, it is possible to work with a longer objective focal length at the same image scale. This allows the camera to be farther from the range of influence of the spray cone;
- darkening of the test stand is not necessary.

Description of the Photographic System

The starting point for the discussion is the principle of operation of the slit shutter.

For rapidly moving objects having image dimensions which are a multiple of the slit width, photography with a slit shutter leads to distortions because the beginning and end of the object image are collected at different times. This effect does not occur in drop photography, however, if the slit width is of the same order of magnitude as the diameter of the drop images. The fact that the drops photographed are imaged successively at different times is insignificant, as the droplet size analysis is a statistical study of a quasi-steady state process in any case.

Both the slit width, s, and the slit velocity, w_s, are decisive for the exposure time, t_B:

$$t_B = \frac{s}{w_s}$$

<u>Shutter elements</u>

The photographic equipment for short time photography in continuous light consists of the slit shutter, which is decisive for the exposure time, and a normal central shutter (main shutter) which is a component of the 150 mm lens provided.

a) Slit disc   b) Segment disc

Figure 12. Elements of the slit shutter.

Figure 12 shows the principal components of the slit shutter. A slit disc, Figure 12a, driven by a motor through flat belt drive, takes on the function of the curtain. The rotational rate of this disc is chosen so that it gives an average exposure time of $t_B = 10^{-5}$ seconds with a slit width of $s = 1$ mm.

A segment disc, Figure 12b, is driven slowly in the opposite direction by a non-slip reduction drive coupled to

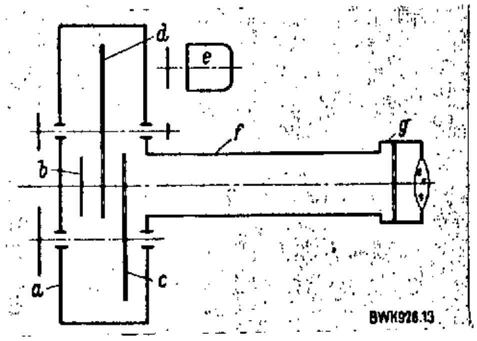

Figure 13: Schematic structure of the recording system.

a. Housing b. Film plane
c. Segment disc (slow)
d. Slit disc (fast)
e. Motor
f. Tube
g. Objective with central shutter.

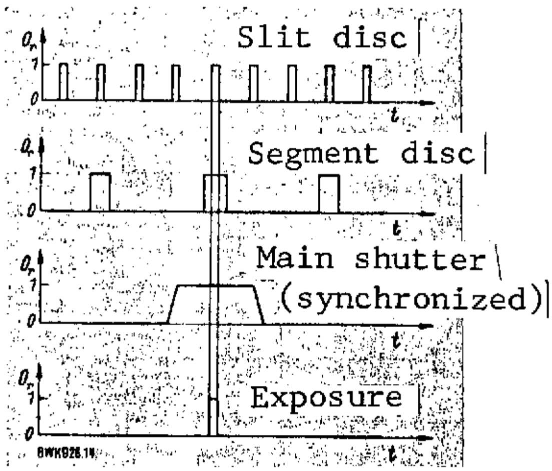

Figure 14. Opening pulse scheme (relative opening o_r).

the fast slit disc. The two discs are displaced from each other, and overlap in the region of the optical axis of the recording system, Figure 13.

The slit and segment are dimensioned and arranged with respect to each other so that the format of the film is covered by the segment disc as soon as the exposure through the slit of the fast disc is complete. The next exposure is possible only when the segment passes the beam again after one rotation of the slow disc. By means of this mechanical frequency division, the "dark period" is extended so that the main shutter has time enough to pass the beam before the exposure and to interrupt it again before the next possible exposure. This prevents unintentional double exposure of the film.

The opening impulse scheme shown in Figure 14 is intended / 318 to explain how the interaction of the shutter elements described above gives a single exposure.

The width of the exposure pulse corresponds to the time which the slit needs to pass over the entire image format. It is about $2.5 \cdot 10^{-3}$ seconds, a multiple of the exposure time, t_B. An opening time of 1/100 second is completely adequate for the main shutter.

Shutter Triggering

The main shutter is coupled with the slit shutter through an electronic trigger, Figure 15.

The starting signal is generated from the segment disc of the slit shutter by means of an inductive transducer (angular velocity, ω). This signal is processed in a two-channel pulse converter, giving positive square-wave pulses with a time separation of $T = 2\pi/\omega$ in each of the two channels (Figure 16).

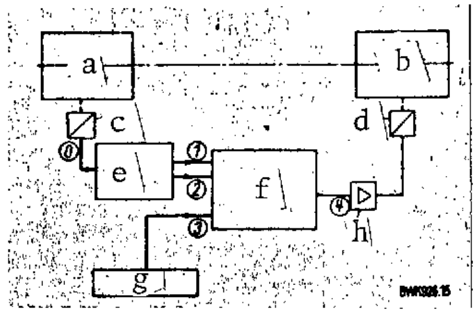

Figure 15. Block diagram of the electronic trigger system.

a - Slit shutter
b - Main shutter
c - Inductive transducer
d - Electromagnet
e - Pulse converter
f - Trigger logic
g - Trigger pulse
h - Amplifier

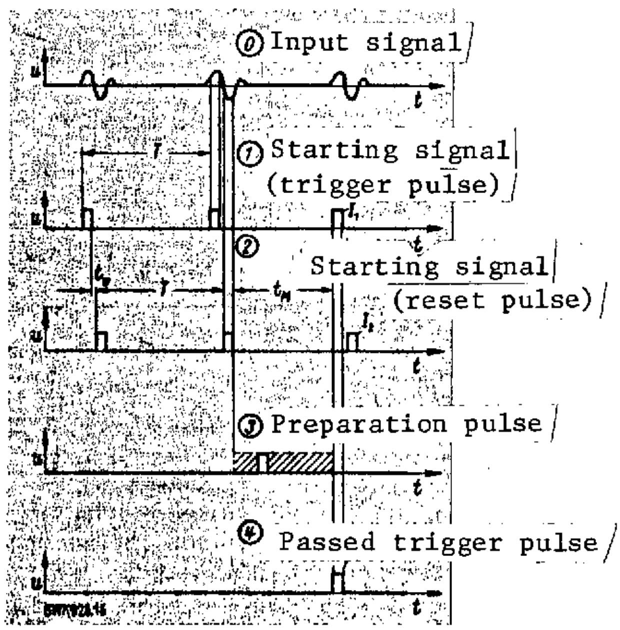

Figure 16. Pulse production in the electronic trigger system.

Each trigger pulse from the starting signal ①, slightly displaced in time by t_v, is assigned to a reset pulse from the starting signal ②. Each reset pulse and the subsequent start pulse delimits a time interval t_M. A preparatory pulse ③ brings the trigger logic to the "watching" position if the starting pulse is confirmed within such a time interval t_M. When the trigger pulse I_1 is delayed after the passage of t_M it is passed through ④ and causes the electromagnetic actuation of the main shutter through an amplifier. The reset pulse, I_2, following the trigger pulse, I_1, causes the bistable flip-flop stages of the trigger logic to return to their initial status after triggering.

Shutter Synchronization

As can be seen from the opening pulse scheme, Figure 14, the main shutter must be synchronized so that it is completely open for the exposure. For this purpose, the inductive pulse transducer at the periphery of the segment disc can be changed in position, Figure 17. In this way, the required "early triggering" can be adjusted.

An electronic synchro indicator serves to check the adjustment. A phototransistor, which temporarily takes the place of the light-sensitive photographic emulsion, serves as the light detector. The short voltage pulse which occurs in the exposure is artificially lengthened with a monostable multivibrator and optically indicated by a glow lamp.

By several test runs, it is possible to determine the two positions, A and B, of the pulse transducer, which produce just one synchronous triggering. In the middle position, $\overline{AB}$ between them, the opening pulse for the main shutter is symmetrically superimposed on the exposure pulse of the slit

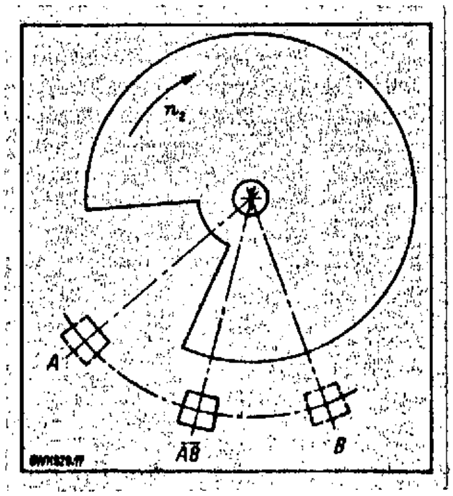

Figure 17. Adjustment of the pulse transducer for synchronizing the main shutter.

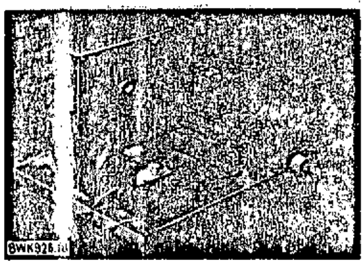

Figure 18. Photographic system for high speed photography in continuous light.

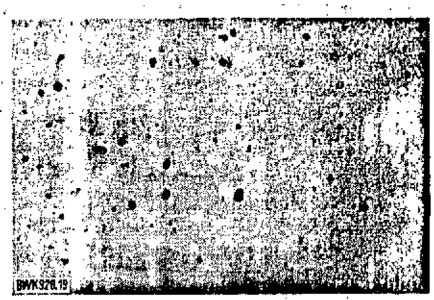

Figure 19. Water droplets in the spray cone of a pressure atomizer with twist (M = 12:1).

shutter, guaranteeing that the whole format will be illuminated evenly.

Testing the Photographic System

Figure 18 shows the operational photographic system. Figure 19 shows droplets from the 60° spray cone of a pressure atomizer with twist at a distance of 70 mm in front of the nozzle. The light source was a 400 watt halogen incandescent lamp. The condensor from a dia-projector was used for concentrating the light. Although the sensitivity of the (panchromatic) photographic material used for the picture was only 17 DIN, the distance between the condensor lens and the photographic objective could be chosen so great (around 700 mm) that the use of air shield nozzles was unnecessary.

Summary

A number of parameters act in the combustion of atomized heating oil. They influence the heat and material exchange in the flame in a complex way. One of these parameters is the state of atomization of the fuel. As the droplet spectra resulting from fuel atomization cannot be calculated, they must be determined experimentally; that is, measured.

Considering the conditions prevailing in heating oil atomization, short-time flash photography was chosen out of the possible measuring methods for drop size determination as / 319 a suitable procedure. Light and heavy oil droplets from the spray cones of various industrial Y-atomizers were photographed in order to test the method practically.

The picture samples are evaluated with an image analysis instrument based on television technology. The results

indicate that the short-time photographic method can be used successfully for droplet size analysis with industrial burners.

Application of the short-time flash photographic method for photography in an atomizer jet raises problems in illumination technology, primarily due to the fact that the light intensity of spark flash devices decrease as the flash time becomes shorter. For this reason, we recommend a photographic system which makes possible the short-time photography of droplets by continuous light.

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